Toward Routine Autonomous Measurement and Interpretation of Optical Variability in Coastal Waters

Marlon R. Lewis
Satlantic, Inc.
Richmond Terminal, Pier 9, 3295 Barrington Street
Halifax, Nova Scotia, Canada B3K 5X8
phone (902) 492-4780 fax (902) 492-4781 email: marlon@satlantic.com

John J. Cullen
Department of Oceanography, Dalhousie University
Halifax, Nova Scotia, Canada B3H 4J1
phone (902) 494-6667 fax (902) 494-2039 email: John.Cullen@Dal.CA
Contract # N0001496C0118
http://www.satlantic.com

LONG-TERM GOALS

Optical measurements can be used for describing oceanographic processes and for developing predictive models. However, a great deal of time and expertise is required for quality control, data management, and interpretation of results. The full potential of optical observation technology for oceanography will be realized only when appropriate measurements can be made routinely, with automatic generation of robust interpretations. Toward that end, our long-term goal is to broaden the utility of radiometric measurements (upwelling radiance and downwelling irradiance) so that turnkey systems can be developed for the generation of derived data, suitable for use by non-experts.

SCIENTIFIC OBJECTIVES

This program of research is aimed at developing and testing ways to interpret water-leaving radiance and downwelling irradiance as measured by radiometer buoys in coastal waters. Complementary measurements with subsurface irradiance sensors (k-chain), profiling and airborne radiometers are also addressed. Efforts are directed toward: (1) refining and testing methods for applying the corrections used in data processing; (2) refining and testing algorithms relating optical measurements to properties of surface waters; and (3) supporting efforts to obtain novel information from radiometer buoys (e.g., taxonomic information for phytoplankton, ultraviolet attenuation and photochemical reaction rates, influence of bubbles).

APPROACH

This work is closely coordinated with the NSERC/Satlantic Industrial Research Chair in Environmental Technology, a partnership between John Cullen (the Chair), Dalhousie University and Satlantic. The Research Chair facilitates collaborative research. This ONR project provides funding for additional technical support from Satlantic which complements Dalhousie-based efforts. Research is conducted with: William Miller (Dalhousie), who is studying the optical properties of coastal waters in relation to photochemical transformations of dissolved organic matter; researchers from NOAA (including P.J. Stabeno and J. Napp), in projects to characterize bio-optical variability in the Bering Sea; and Maureen Keller (Bigelow Laboratory), looking at optical variability in estuarine and coastal waters of Maine. The approach is to pursue basic questions in bio-optics during collaborative research cruises and to use this ONR-sponsored effort to improve technologies for measurement, data analysis and interpretation. Integrated with this is are the university-based research programs of Lewis and Cullen, directed toward improved interpretations of near-surface optical measurements.

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WORK COMPLETED

Measurements of reflectance and attenuation. Near surface reflectance in the UV and visible was measured with a 14-channel radiometer buoy while diffuse attenuation was measured in 13 channels with a profiling radiometer and discrete samples were taken to characterize the optical properties and constituents of the water. Several methods were used to analyze the data objectively (e.g., Sildam et al. 1998). Deployments were made during: 4 cruises in coastal waters of Maine (with Maureen Keller); a cruise off the east coast of the U.S. (William Miller, Dave Kieber, Ken Mopper); an intercalibration exercise in coastal waters of Norway (Howard Browman); and eight times during a study in coastal waters of Nova Scotia. Data from these deployments are being used to develop empirical relationships between near-surface reflectance and attenuation in UV and visible wavelengths. These relationships are at the core of our models relating biological and photochemical processes to ocean color (see *Ultraviolet Radiation*, below). Data on optical properties and constituents of the waters are used to improve bio-optical models (e.g., Ciotti et al. 1999a).

Phytoplankton communities and optical properties of coastal waters. Semi-analytical expressions were developed to describe quantitatively how idealized phytoplankton assemblages could affect apparent optical properties (AOPs), such as diffuse attenuation and surface reflectance (Ciotti et al. 1999a). Spectral absorption by phytoplankton, as well as backscattering and absorption by other optically active components, were parameterized as functions of chlorophyll+phaeopigment concentration, C, consistent with large data sets from the lab and field. The model reproduced central trends in apparent optical properties with C and agreed to within 20% of empirical models that relate diffuse attenuation to radiance ratios within a range of C between 0.5 and 30 mg m^{-3}. Variability in the spectral shape of the absorption coefficient in distinct communities of surface phytoplankton was related to cell size and taxonomic composition. More than 95% of the variability in spectral shape of all observed spectra was accounted for when phytoplankton absorption was parameterized using two constant spectral shapes (one for small cells, one for large) and a size parameter (Ciotti et al. 1999b). Apparent optical properties could therefore be estimated by specifying cell sizes of phytoplankton dominating the community. Forward modeling was used to select relationships between diffuse attenuation and ratios of surface reflectance with minimum influence of backscattering and CDOM plus detrital absorption, hence maximal influence of phytoplankton absorption as influenced by dominant cell size (Ciotti 1999). This approach provided a tool to observe and monitor changes in the nature of a phytoplankton community (i.e., dominant cell size) using optical measurements only.

Ultraviolet radiation. Our techniques for describing quantitatively the effects of UV radiation on biological processes were applied in four collaborative studies addressing the effects of UV on copepods and fish larvae (Kouwenberg et al. 1999a,b; Browman et al. 1999; Kuhn et al. 1999), and our model of UV effects as influenced by vertical mixing was modified substantially and used to describe the effects of vertical mixing on UV-induced damage to DNA in bacterioplankton (Huot et al. 1999). Enough data from our optical stations were obtained and analyzed to support several studies relating ultraviolet attenuation, absorption, and photochemical transformations in surface waters to reflectance in visible wavelengths (Cullen et al. 1999; Johannessen et al. 1999; Nieke and Cullen 1999a,b. See also the report of W.L. Miller). More progress was made on our method for estimating UV attenuation and photochemical transformations from visible reflectance (Cullen et al. 1999): the spectral effects of clouds on UV- as well as visible irradiance was characterized empirically from our measurements in the Bering Sea, so that measurements in one waveband (490 nm) on an ocean-color drifter could be used to estimate spectral solar irradiance in the visible and UV wavebands. This estimation is essential for calculating spectral reflectance and effects of UV radiation when measurements of spectral solar irradiance are unavailable.

Fluorescence of Phytoplankton. We developed a device to characterize changes of variable fluorescence (i.e., F_o and F_m, measures that are used to estimate photosynthetic capabilities of phytoplankton) vs irradiance as a function of time (Parkhill et al. 1999). These measurements can be used to relate sun-induced chlorophyll fluorescence to photosynthesis, nutrition and light history of phytoplankton *in* *situ*. A goal is to infer characteristics of phytoplankton communities from remote sensing of chlorophyll fluorescence.

RESULTS

Áurea Ciotti's research showed that mechanistic approaches to interpreting bio-optical data are feasible by the use of simple parameters, combined with semi-analytical models, that relate optical signatures to ecological features of phytoplankton (Ciotti 1999). The semi-analytical model of ocean color and attenuation as a function of trophic status (SAMOCAFOTS; Ciotti et al. 1999a) incorporates well-documented bio-optical relationships into an internally consistent description of how optical properties of surface waters changes as a function of chlorophyll concentration. It thus addresses a number of key issues that are central to our efforts toward developing robust interpretations of optical measurements in surface waters. The strong consistency of model predictions with ocean-color algorithms and empirical relationships between AOPs shows that the model is a powerful tool for predicting and possibly detecting the influence of different phytoplankton communities (i.e., particle assemblages with absorption and scattering properties different from the central trend) on relationships between ocean color, diffuse attenuation, and chlorophyll concentration. We learned that key properties of phytoplankton (pigment composition and the package effect) changed consistently with dominant cell size of the phytoplankton so that spectral absorption by phytoplankton could be described well by one parameter, constrained with two end-member spectral shapes and scaled by absorption at one wavelength. It is thus easy to describe how phytoplankton communities of different dominant cell size influence bio-optical relationships. Efforts to find relationships between AOPs that were strongly sensitive to dominant cell size and weakly influenced by CDOM+detrital absorption (a major complicating factor) were not entirely successful, but they demonstrated the utility of the approach. Results indicated that measurements at more wavelengths (e.g., hyperspectral reflectance) might provide enough information to use optical measurements for detecting aspects of phytoplankton community structure.

We demonstrated that measurements of upwelling radiance in the visible (ocean color) can be used to quantify UV-dependent processes in aquatic systems (Cullen et al. 1999): 1) attenuation coefficients for UV and visible irradiance are estimated from spectra of upwelling radiance at the surface, based on empirical relationships between ratios of upwelling radiance and near-surface diffuse attenuation coefficients; 2) total absorption is related to attenuation by accounting for geometry of the radiance field; 3) total absorption is partitioned among colored dissolved organic matter (CDOM; essential to photochemistry), water, and particulate matter using published coefficients for water, estimates of chlorophyll from blue:green reflectance ratios, and assumed chlorophyll-specific particulate absorption spectra; 4) solar irradiance at the surface is calculated from a clear-sky model, adjusted with a relationship describing the spectral effects of clouds as a function of measured/modeled irradiance in the visible; and 5) laboratory-derived action spectra, modeled irradiance, and estimated CDOM vs total absorption are used to quantify rates of photochemical transformation or biological action.
This year, we parameterized our model with data from several marine environments, along with an action spectrum for photochemical production of carbon monoxide from CDOM, to estimate the photochemical production of CO using aircraft remote sensing of ocean color and measurements of ocean color from drifters. This approach, used in conjunction with our model of UV effects as influenced by vertical mixing (Huot et al. 1999a,b) can be used to estimate depth-dependent, UV-induced photochemical and biological transformations from remote sensing of ocean color.

IMPACT/APPLICATIONS

The research associated with this project, along with rapid advances by other workers, is moving us steadily toward achieving the stated goal of developing turnkey systems for measuring upwelling radiance and downwelling irradiance in surface waters and delivering derived data on water clarity and variability of important constituents of surface waters. No definitive procedure for inferring phytoplankton community structure from ocean color was developed, but our models provide important guidance for the development and evaluation of future approaches. Research on ultraviolet radiation in surface waters has revealed great potential for new applications in remote sensing and autonomous observation systems. The link between ocean optics and UV research (photochemistry and photobiology) will continue to strengthen in the next few years.

TRANSITIONS

Interest in this work is reflected in frequent inquiries from colleagues, requests to deliver talks (including a keynote talk at an IUGG special session), invitations to participate in workshops (e.g., U.S. Coastal Ocean Observing System workshop), and appointment of J. Cullen as chair of an international workshop to develop plans for the GEOHAB program on harmful algal blooms. This new international program was approved: it will have direct links to the Global Ocean Observing System, with a strong potential for further development of bio-optical studies in coastal waters.

Our procedures for modelling the effects of ultraviolet radiation on biological and photochemical processes in surface waters have generated interest, and we have supplied our code to four groups (Howard Browman, Janet Campbell, William Miller, Ken Mopper) for use in their research.

RELATED PROJECTS

1) NSERC/Satlantic Industrial Research Chair: this partnership is the central source of support for instrumentation, field work, lab studies, and university salaries. Funding for complementary projects, such as this ONR program, are highly leveraged by the research partnership.

2) W.L. Miller, Dalhousie (ONR): photochemical processes and optical properties of surface waters. We participate in the cruises, share data, and collaborate on analysis. Our modelling efforts are directly relevant to their objectives. Miller focuses on photochemical processes, we emphasize optical properties. His group is making rapid progress using their own data interpreted and analyzed collaboratively with us.

3) NOAA-funded work in the Bering Sea (J. Cullen and R. Davis): optical observations from ships, moorings, drifters and aircraft are used to describe bio-optical variability in the Bering Sea as related to physical forcing (P.J. Stabeno, NOAA) in the context of fisheries oceanography (J. Napp, NOAA). Funding from ONR allows us to append research on UV radiation, photochemistry, and fluorescence.

4) ONR-funded research by Marlon Lewis and colleagues (HyCODE). This recently established project is discussed in a separate report, in which Lewis's activities are described in more detail. We share data and discuss results for these complementary activities.

5) Research on harmful algal blooms (with Don Anderson, WHOI), partially funded by NSERC and the ECOHAB program, provides information on physiological and optical characteristics of phytoplankton (including fluorescence) that is directly relevant to bio-optical characterization of coastal waters. We are now incorporating measurements of absorption, scatter (WET Labs ac-9) and backscatter (HOBI Labs Hydroscat; in collaboration with P. Hill, J. Grant and A. Hatcher at Dalhousie) into our laboratory program

PUBLICATIONS

Refereed publications

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Huot, Y., W.H. Jeffrey, R.F. Davis and J.J. Cullen. 1999a. Damage to DNA in bacterioplankton: A model of damage by ultraviolet radiation and its repair as influenced by vertical mixing. Photochem. Photobiol. (*in revision*).

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Huot, Y. 1999. Damage to DNA in bacterioplankton: A model of damage by ultraviolet radiation and its repair as influenced by vertical mixing. M.Sc. thesis, Dalhousie University.

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Cullen, J.J., R. F. Davis, B. Nieke, S. Johannessen and W. L. Miller 1999. Estimating UV attenuation and photochemical reaction rates from remote sensing of ocean color. XXII General Assembly, IUGG, IAPSO Symposium on “Optical Oceanography & UV Radiation,” Birmingham. (invited)

Huot, Y., J.J. Cullen, J.J., W.H. Jeffrey, 1999b. A model for DNA damage and repair in bacterioplankton as influenced by vertical mixing. 1999 ASLO Winter Meeting, Santa Fe.

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